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14. ABSTRACT

Elastic memory composites, or EMC, can be folded by applying a load that forcibly folds the material into the desired, packaged shape while at an elevated temperature above the polymer's glass transition temperature. The deployment performance and repeatability was sufficiently quantified for this EMC laminate. An analysis method was devised that allows a designer to obtain an approximation for the maximum achievable curvature a laminate can achieve given any combination of fiber and resin.

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Micromechanics of Smart Materials for Large Deployable Mirrors
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Extended Abstract

Current and future spacecraft and satellite designs are increasingly including large, ultra-lightweight structures and components that must be efficiently packaged for launch and reliably and precisely deployed for use once in space[1]. Elastic memory composites, or EMC, can be folded by applying a load that forcibly folds the material into the desired, packaged shape while at an elevated temperature above the polymer's glass transition temperature, T_g. To deploy, the EMC material is again reheated above the T_g, wherein the material returns to its original, as-cured shape.

The limiting factor that dictates the deployment accuracy of this material is the micro-buckling of the individual fibers. The kinematics of this micro-buckling dictates whether or not the laminate behaves elastically, or if fibers break. This report presents the experimental methods used to characterize the deployment repeatability and performance of an EMC laminate as well as the fiber level effects of repeated deployment.

Research Objectives

- Quantify the deployment accuracy. In the case of a hinge folded through a known radius of curvature (angle), this can be quantified as an "un-recovered" angular value, which can then be interpreted as a % recovery of the original induced angle.
- Obtain a relationship between material property degradation and both induced packaging strain and repeated deployment cycles.
- Obtain an analysis method that allows a designer to obtain an approximate upper limit for the maximum amount of curvature that a laminate can achieve given fiber and resin properties.

Testing and Results

The EMC test material consisted of 12 8"x1" unidirectional coupons with a fiber volume fraction of 40%. The twelve coupons were evenly split between two-ply and four-ply laminates. The laminates were reinforced with T300 carbon fibers, and the matrix material was DP-7 EMC resin, which is an epoxy based thermoset resin[2]. This resin had a glass transition temperature of approximately 70°C. Testing was conducted at 100°C to ensure that bending was done within the full soft-resin state of the polymer.

The deployment precision study involved characterizing both the deployment precision of the EMC coupons at varying bending strains under near-zero resistance as well as the deployment repeatability due to increasing bending and deployment cycles. The primary variable for this test was the bend ratio, β, or the ratio of bend radius to material thickness, which is also inversely related to the maximum effective strain[2].

$$\beta = \frac{t}{R} = \frac{1}{\varepsilon_{eff}} \qquad (1)$$

Tests were conducted at bend ratios of 2.5, 5, 10, 20, 40, and 80. All possible bend ratio combinations are shown in Table 1 based on the material thickness and bend radius of the test fixtures. Each deployment test was also conducted a total of 5 times in order to characterize the material's deployment repeatability performance. Figure 1 shows the test fixture that was used for the non-tension tests.

	Bend Radius				
Laminate Thickness	0.125"	0.25"	0.5"	1.0"	2.0"
(2-Ply) 0.025"	5	10	20	40	80
(4-Ply) 0.05"	2.5	5	10	20	40

Table 1: Deployment Precision Test Matrix

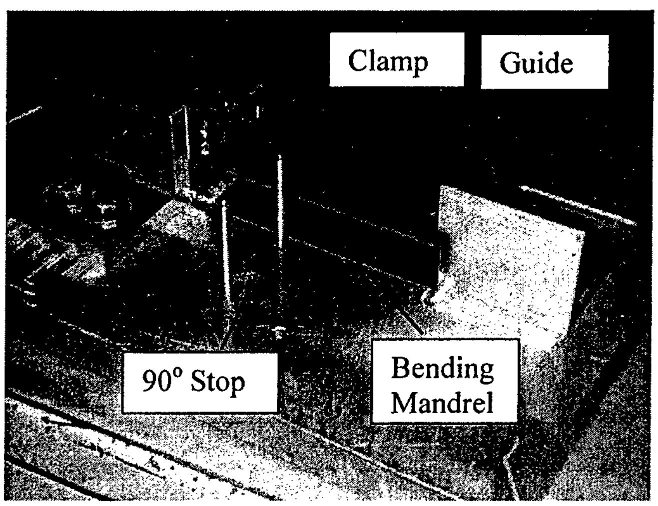

Figure 1: Non-Tension Bending Apparatus

The results from the non-tension tests are shown in Figure 2. The data does not reveal a discernable trend although the % recovery does fall within a range of approximately +/- 2%, which is considered very encouraging. However, the occurrence of over-deployment or, % recovery exceeding 100%, was not expected.

Non-Tension Deployment Precision

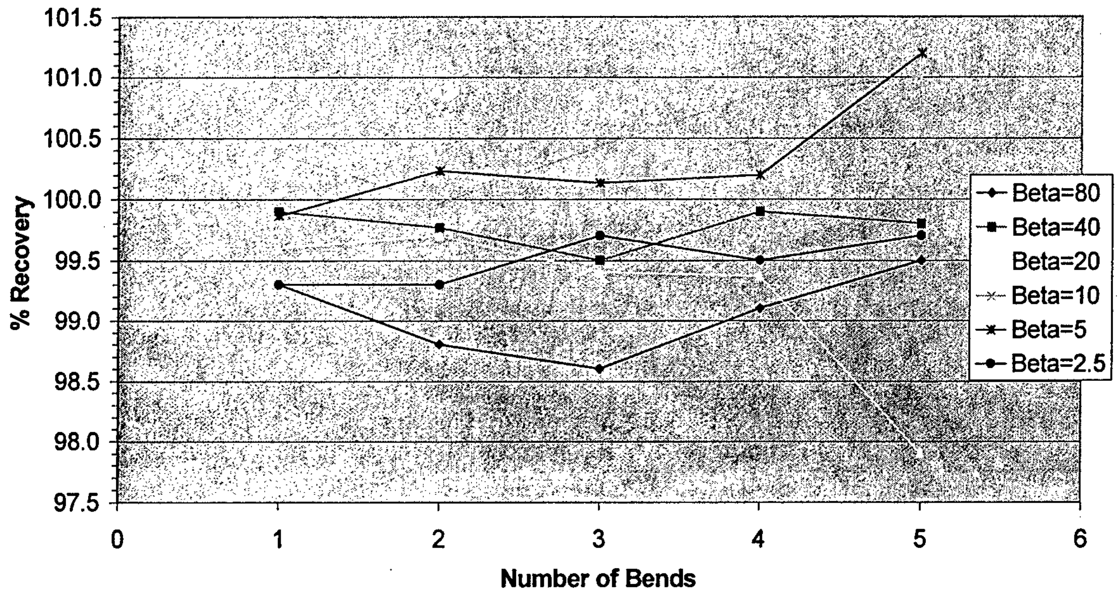

Figure 2: Non-Tension Deployment Precision Results

<u>Fiber Damage Investigation</u>

Each coupon was inspected using an optical microscope following the completion of the deployment precision and repeatability tests. This investigation revealed observable damage in only those coupons tested at bend ratios of 20 (ε_{eff}=0.05) or less. Additionally, fiber damage was only observed on the compression side of the bend. In-plane micro-buckling was only observed in the β = 20, non-tension test, which is shown in Figure 3. However, fiber fracture was observed in the tension test at the same bend ratio. Based on this difference, it was assumed that the minimum achievable bend ratio without fiber damage was 20. Therefore according to Equation 1, the critical effective strain, or the effective strain at which fiber fracture occurs, is 0.05. It should also be noted that it was originally theorized that the application of tension during bending decreases fiber damage, which is counter to this result.

The in-plane micro-buckle shown in Figure 3 can be quantified using the T300 fiber's known diameter of 8 microns. Using this constant, an approximate micro-buckle wavelength and amplitude range of 0.64-0.40mm and 0.088-0.048mm respectively was obtained. It should be noted that a wavelength is defined here as one-half of a sine curve, or the distance between two inflection points.

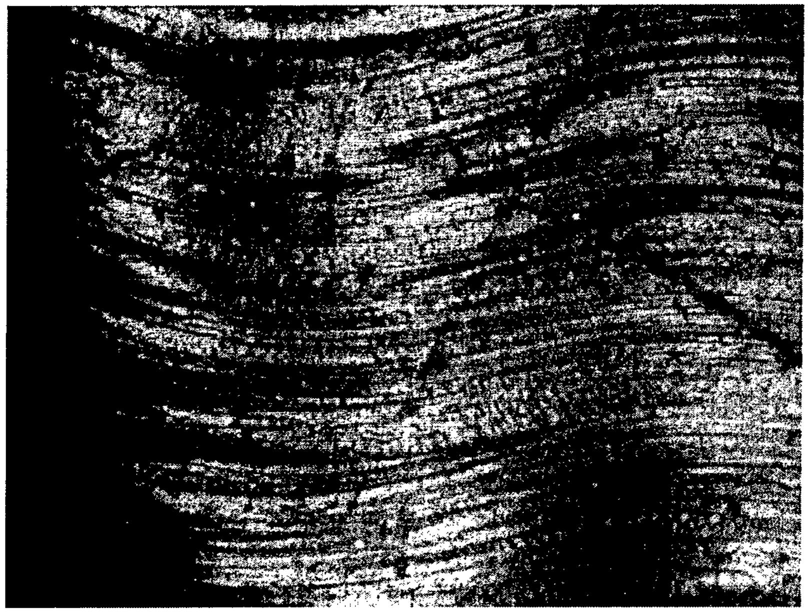

Figure 3: In-Plane Micro-Buckling in the $\beta = 20$, Non-Tension Test

Kinematic Analysis[3]

As previously stated, the goal of this analysis is to obtain an approximation for the maximum effective strain an EMC laminate can achieve given fiber and resin properties. The end result was a two-fold analysis consisting of both a stability and kinematic analysis with a related intermediate variable defined here as the critical wavelength or, the minimum wavelength a fiber can achieve prior to fracture. The critical wavelength, λ_{cr}, is a material property based on the fiber's failure strain.

Equation 2 shows the relationship between the effective strain and the wavelength to amplitude ratio for a sinusoid if the axial strain is neglected[2].

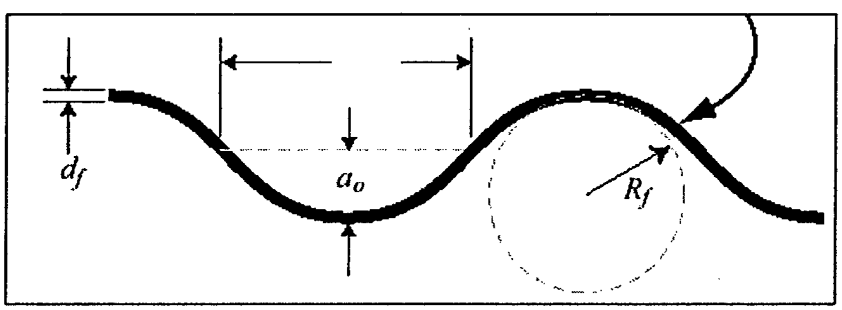

Figure 4:The Sinusoid Profile of a Micro-Buckled Fiber

$$\varepsilon_{effective} = \frac{1}{1+\frac{4}{\pi^2}\frac{\lambda^2}{a_o^{\,2}}} \qquad (2)$$

Equation 2 results in an effective strain range of 3.4 to 4.5% based on the observed range of the amplitude to wavelength ratio, which may be considered reasonably close to the approximated value of 5% based on the inverse of the bend ratio. Additionally, one would expect Equation 1 to over predict the effective strain since it neglects the contribution from the tension fibers.

The maximum achievable curvature for T300 fibers is 0.40mm obtained assuming an r_f of 4 microns and an ε_{fail} of 0.01. The kinematic relations[3] results in a wavelength of 0.58mm assuming that the effective failure strain corresponding to the minimum achievable curvature is 0.05. This wavelength clearly falls within the observed range of 0.64 to 0.40mm.

<u>Stability Analysis</u>

Much of this analysis is based on Timoshenko's solution for the buckling load of a bar on an elastic foundation[4]. Timoshenko's solution models the elastic medium as a series of axial members with a certain spacing and stiffness. He derives expressions for both the strain energy due to bending of a bar with stiffness EI and length *l*, and ultimately derives an expression shown in Equation 3 for the critical load for this column or, the load at which buckling of the bar occurs.

$$P_{cr} = \frac{\pi^2 EI}{l^2}\left(m^2 + \frac{\beta_n l^4}{m^2\pi^4 EI}\right) \qquad (3)$$

The variables m and β_n refer to the number of half sine waves in the buckled shape and the stiffness of the foundation respectively. A similar energy method is now used to obtain approximations for both the value of β_n for a fiber within a laminate and ultimately the maximum achievable micro-buckle magnitude based on the laminate's material properties.

Shearing occurs between fibers of adjacent layers as a result of the varying bending strain through the laminate's thickness. It can be shown that the shear energy per unit length for this element is represented by Equation 4 where δ is the distance between adjacent fibers, G is the resin's shear modulus, and t is the thickness of the laminate.

$$U_1 = \frac{1}{2}\left(\frac{a_n}{t}\delta\right)^2 G \qquad (4)$$

The energy equations can now be minimized with respect to the buckled shape, *m*, to obtain the wavelength corresponding to the lowest energy mode. The results can be simplified with the terms rearranged to show that Equation 5 represents the critical micro-buckle wavelength.

$$\lambda = \sqrt[4]{\frac{\pi^4 EI}{3G\left(\frac{\delta}{t}\right)^2}} \qquad (5)$$

Equation 5 results in a wavelength of approximately 1.3 mm based on a soft resin shear modulus of 1000 psi and T300 fiber properties. The shear modulus was obtained from a Dynamic Mechanical Analyzer (DMA) test conducted on a block of neat DP-7 resin. This wavelength is approximately twice the micro-buckle wavelength estimated from Figure 3. This difference may be attributed to the apparent extreme temperature sensitivity of the resin's shear modulus. A temperature of 95°C would result in a shear modulus that is approximately two and a half times the shear modulus corresponding to 100°C. This 5°C drop in temperature would result in a critical buckle wavelength of approximately 1.0 mm.

Conclusions

The deployment performance and repeatability was sufficiently quantified for this EMC laminate. This property is clearly shown to be a function of the induced bending strains. The application of tension during bending was also shown to be a significant contributor to the deployment performance, although the practicality of incorporating tension into a deployment structural system was not investigated.

The analysis portion of the study yielded satisfactory results. An analysis method was devised that allows a designer to obtain an approximation for the maximum achievable curvature a laminate can achieve given any combination of fiber and resin. This was achieved using a combination of kinematic and stability analysis. Additionally, the analysis results were checked with reasonable success using the test results.

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